LA-UR -86-4184

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DE87 003733

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SUBMITTED TO 11th Int. Conf on Electromagnetic Isotope Separators and Techniques Related to Their Applications
Los Alamos, NM
August 18-22, 1986

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Los Alamos, New Mexico 87545

The Time–of–Flight Isochronous (TOFI) Spectrometer for Direct Mass Measurements of Exotic Light Nuclei

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A new type of time–of–flight recoil spectrometer designed to measure the masses of neutron–rich light nuclei has recently been completed at LAMPF. The spectrometer relies on an isochronous design that directly correlates an ion's time–of–flight through the spectrometer with it's mass–to–charge ratio. Additional measurements of the ion's velocity and energy enable the charge state of the recoil to be uniquely defined and thus permit precision mass measurements given sufficient statistics. The performance of the spectrometer has been investigated in both off–line (using alpha sources) and on–line tests. The design resolution of $\Delta M/M = 1/2000$ (FWHM) has been achieved. Initial performance results of the spectrometer are descrit ed with emphasis placed on the techniques used to achieve the overall high mass resolution and large solid angle/momentum acceptance.

1. Introduction

Measurements of ground–state masses are of fundamental importance to the understanding of nuclei since they manifest all interactions that contribute to nuclear binding. Features such as the finite range of the nuclear force, nuclear pairing, nuclear shell structure, and the macroscopic, shape–dependent properties of nuclei were first identified from systematic studies of the nuclear mass surface. Nuclear masses also serve as important constraints for nuclear mass theories whose predictive capabilities are essential to astrophysical calculations of the natural abundance of elements within the universe. This importance has encouraged an experimental program of mass measurements, especially for nuclei far from the valley of beta stability, where increasing deviations from theory have been observed. Until recently such mass measurements have been hampered by the short half–lives and limited production rates of these exotic nuclei (e.g. fewer than 15 new masses were measured for the first time in the $Z \leq 20$ region from 1976–1985). In this paper we present an overview and description of the Time of Flight Isochronous (TOFI) spectrometer[1] that has been built expressly to overcome the many limitations of previous mass measurement techniques and make large scale, systematic mass measurements of light Z neutron–rich nuclei.

2. TOFI The Time of Flight Isochronous Spectrometer

Our approach uses a new type of spectrometer that combines a fast recoil technique with the direct

mass measurement method. An isochronous design is employed for the spectrometer that causes the transit time of a particle with a given mass–to–charge ratio passing through the spectrometer to be independent of the particle velocity. This condition is achieved by an arrangement of sector magnets that transmits ions of equal mass–to–charge ratio but differing velocities on trajectories of different lengths, such that the overall flight time is the same (see Figure 1). The corollary to this velocity independence is that the flight time is then a direct measure of an ion's mass–to–charge ratio. In addition to this isochronous property, TOFI is overall momentum nondispersive and focuses all ions to a single small spot.

Advantages of a recoil spectrometer of this type include the ability to simultaneously measure the masses of many neighboring nuclei, including both previously unmeasured nuclei that lie far from the valley of β–stability and known nuclei with well determined masses that can be used as internal calibration points. The broad mass–to–charge acceptance of the spectrometer is well matched to the high–energy, proton–induced fragmentation reactions which produce a large variety of neutron–rich nuclei. In addition, the technique is fast ($t_{1/2} > 2\mu s$), element nonspecific, and does not require knowledge of the decay scheme (provided there exist no long–lived isomeric states). Finally, only one high precision measurement (i.e. the time–of–flight through the spectrometer) is needed to determine the mass of an ion.

2.1 Secondary Beam Transport Line

TOFI is connected to a secondary beam transport line (see Figure 1 of Ref. 2) that captures a small fraction of the recoils produced via fragmentation reactions induced by the interaction of the 1 mA, 800 MeV proton beam of the Los Alamos Meson Physics Facility with a 1.0 mg/cm^2 Th target. These recoils are transported to the spectrometer after passing through a mass–to–charge filter that largely eliminates the high intensity of uninteresting light ions which normally would enter the spectrometer. The transport line has an overall image magnification of 2 that matches a large solid angle to the phase space acceptance of the spectrometer. (See Ref. 2 for further details.)

2.2 Spectrometer Optical Design

To achieve the desired isochronous design a four unit cell approach was used which has the property

that all first order optical aberrations are zero and higher order aberrations to a large extent are minimized[1]. More specifically, TOFI consists of four homogeneous mirror-symmetric sector magnets, each having an 81° deflection angle, equal entrance and exit angles of 23.3°, and identical field-free drift distances (0.98 m) before and after each sector magnet (see Figure 2). This design assumes that the ions have energies of ~2 MeV/amu as are typical for recoils that are produced in proton-induced heavy-target fragmentation reactions. Summing up all the aberrations inherent in the optical design, one obtains a maximum deviation in the flight time of approximately 0.08 ns out of a typical flight time of ~600 ns. Recalling that the time-of-flight is directly proportional to mass-to-charge, a mass resolving power ($M/\Delta M$) of 2000 was taken as the initial design goal assuming a total timing uncertainty of 0.30 ns which was expected to be dominated by the timing detector resolution. Additional specifications for the spectrometer are given in Table 1.

2.3 Dipole Magnets

In order to reach the resolving power, the sector magnets had to be fabricated to high tolerance ($\Delta B/B \sim 10^{-4}$). This requirement is clear from Figure 1 where ions traveling along different trajectories must experience the same magnetic field. Imperfections in the second and third dipole magnets are of special concern to the isochronicity of the spectrometer since the momentum dispersion is largest in these magnets. Rose shims were used to increase the radial width of the uniform field region (defined by the magnetic field being uniform to ±1 G out of 6000 G) from 15 cm to 20 cm for a pole width of 30 cm and a magnetic gap of 9.6 cm. Iron wedges were used to define the entrance and exit effective field boundaries to a flatness of ±0.4 mm over the entire useable pole width of 20 cm with the correct edge angle. Figure 3 shows both top and side views of one sector magnet and indicates the locations of the Rose shims, iron trimming wedges, and surface coils (described in the next section).

2.4 Surface Coils

Two types of surface coils were constructed, using printed circuit board technology, to empirically tune the uniformity and shape of each magnet. The first type of surface coil was designed explicitly to reduce the inhomogeneities remaining in the magnetic field[3]. The second type of surface coil was designed to superimpose either a quadrupole or hexapole field on top of the main magnetic field[4].

Altogether 16 surface coils were fabricated, an inhomogeneity coil and a quadrupole/hexapole coil for every pole tip. Each double sided coil is 1.6 m long, 30 cm wide, with 0.5 mm of copper plated on both sides of a 0.75 mm thick G–10 board. The original designs for the surface coils were drawn full–scale on mylar using a computer and transferred photographically to the printed circuit board photoresist. A brief summary describing the coil design and their performance follows.

2.4.1 Inhomogeneity Surface Coils

Each inhomogeneity surface coil was designed empirically from a magnetic field map taken near the top or bottom magnet pole piece for which the coil was intended. Mapping of the pole–tip magnetic fields was especially difficult because of the dual requirements for obtaining 0.1 G accuracy in the homogeneous portion of the field and for extending the map into the fringing field regions of the magnet with lower resolution. A new field–mapping technique that acquires two field maps simultaneously was developed to accomplish this dual goal.

The first map was determined by a nuclear magnetic resonance (NMR) magnetometer to measure the field, and the second map used a temperature–stabilized Hall–probe that was mounted directly on top of the NMR sensor. The NMR field map was accurate to considerably better than 0.05 G, but could not obtain data in the fringe fields of the magnets. The Hall–probe map covered the entire region that needed to be mapped, but was accurate to only 5 G absolute. A composite field map was produced by using the NMR map where the magnetometer was stable and by filling the remaining regions with a corrected Hall–probe map. This correction consisted of finding the two most recent data points where both the NMR and Hall–probe fields were valid and then normalizing the Hall–probe data to the NMR data. In this fashion, the Hall–probe data were continuously recalibrated on an absolute scale, yielding fringing field data with an accuracy of 0.5 G.

The resulting field maps for the top and bottom poles were modified in several ways in order to create the final contour maps needed to design the surface inhomogeneity coils. First, the maps had to be extended, using a linear extrapolation routine, to regions that could not be reached by the field mapping probes because of obstructions. Second, a boundary region was defined around the map that was 3.2 cm wide and located 3.2 cm away from the effective surface coil outer edge. Outside this

boundary region the map was set to a constant value; inside, the map was set to the measured field value. The values of the data points within the boundary region itself were determined by doing a linear interpolation across the boundary. In this fashion the contour lines of the field map could be smoothly closed. Third, the maps were smoothed several times using a technique that averaged adjacent data points to redetermine the value of the central data point. Finally, the maps were drawn full-size with the contours in one place being cut and reconnected to form a spiral so that current was fed in at one point of the circuit board and exited at another. The final contour spacing was 0.75 G, which was limited by the minimum width acceptable for a current path. This contour spacing produced a field of approximately 0.75 G uniformity, which improved the field homogeneity by at least a factor of three.

2.4.1 Quadrupole and Hexapole Surface Coils

The quadrupole/hexapole surface coils were designed from theory[4] and are identical for all magnets. Figure 4 is a photograph of a quadrupole coil lying on the bottom pole tip of one the dipoles. (The hexapole coil is etched on the reverse side of the same printed circuit board.) Figure 5 shows the effects of these surface coils on the energy dependence of the time–of–flight measured through the spectrometer for 5.4 MeV alphas originating from the decay of ^{241}Am. Recall that for the spectrometer to be isochronous the time-of-flight should be velocity independent (i.e. energy independent for the same particle type) and the data points in Figure 5a should thus form a horizontal line. The effect of the quadrupole coils located in magnets 2 and 3 are to superimpose a linear energy dependence on the transit time through the spectrometer (see Figure 5b). From Figure 1 it should be noted that the quadrupole coils in the second and third magnets (where the momentun dispersion is greatest) will have the largest effect on reducing chromatic aberrations, while the quadrupole coils in the first and last magnets mainly aid in providing a sharp image at the exit of the spectrometer, thus insuring a high transmission. A quadratic energy dependence is superimposed on the alpha particle transit times by the hexapole coil as demonstrated in Figure 5c. Figure 5d shows the energy dependence of the time of flight after optimizing the currents in all the surface coils. The energy dependence is almost entirely removed and the scatter in the data is now dominated by the timing detector resolution (0.18 ns). Overall the surface coils reduced the FWHM of the time peak from 0.30 ns to 0.20 ns.

2.5 Control and mechanical details

TOFI and the secondary beam transport line use an Allen/Bradley[5] microprocessor system for control purposes. This extremely versatile and reliable system is designed around a small computer that controls remote I/O racks into which CAMAC–like input/output modules may be inserted. All interlocks, status lights and on/off commands for the vacuum system and power supplies are controlled by the Allen/Bradley microprocessor. A 500 A – 200 V power supply is used to power the four spectrometer magnets that are connected in series. Small current shunts on each magnet are used to make minor adjustments so as to match the fields of the four magnets. An appreciable long–term drift in the main supply current necessitated the installation of an NMR feedback circuit that has improved the long–term field stability ($\Delta B/B$) from $1\text{x}10^{-3}$ to $2\text{x}10^{-5}$. The alignment of TOFI was done using a computer–controlled stereo surveying system which enabled each magnet to be positioned in three dimensions to a tolerance of ± 0.5 mm. Finally, TOFI is designed to run at a pressure of $5\text{x}10^{-7}$ mbar in order to reduce residual gas scattering and charge exchange reactions to an acceptably low level. To accomplish this, two ion pumps of 500 liter/s and three cryogenic vacuum pumps of 1500 liter/s were employed to evacuate the spectrometer, which utilizes stainless steel vacuum chambers connected by aluminum seals throughout.

2.6 Achieved Performance

Unfolding the resolution of the timing detectors one obtains an intrinsic resolving power for the spectrometer of ~6000 based on our first experiment. The actual timing resolution was approximately 0.23 ns for this experiment and was largely dominated by the intrinsic resolution of the timing detectors and drifts in the magnetic fields. This resolution results in a mass resolving power of 2600, easily exceeding the initial design goal of 2000. Figure 6 shows a typical mass–to–charge histogram for a single element with a given charge state (e.g. Na^{9+}). Note the clean separation between peaks without background and the presence of both calibrants and unknowns in the same spectrum. Improvements in both magnetic field stability and timing detector resolution should enable further increases in the resolving power.

The focusing and transmission characteristics of TOFI have been examined using a position sensitive,

multi–step, multi–wire proportional counter[6]. Visually one observes that the focus is essentially a one–to–one image of the source, as originally designed. In addition, transmission tests show that the spectrometer transports better than 85% of the ions presented to it by the transport line for ions within the momentum–to–charge acceptance of the system (defined by a collimator located at the spectrometer midpoint). These focusing properties and high transmission characteristics were readily achieved by setting the four dipole magnets to the same field and then making slight current adjustments to the individual shunts. The surface coils were found to have only a weak effect on overall focusing and transmission properties and so were used mainly to improve the isochronicity of the spectrometer as described above.

3.0 Direct Mass Measurements

In this Section, we briefly describe how a mass is obtained experimentally using the TOFI spectrometer. The detector arrangement consists of three fast timing detectors located at: 1) the midpoint of the transport line, 2) the entrance focus to the spectrometer and, 3) the exit focus of the spectrometer. These timing detectors are secondary–electron, microchannel–plate detectors that detect the electrons emitted when an ion passes through a thin ($\sim 30 \mu g/cm^2$) carbon foil[7]. They employ an isochronous design that accelerates the secondary electrons and bends them 180° where they impinge onto a set of microchannel–plates which amplify the signal. A total energy and Z identification detector is located immediately after the third timing detector at the exit of the spectrometer. This detector may consist of a solid state detector telescope, a gas ionization detector, or a Bragg spectrometer. The primary goal of this detector is to obtain good energy resolution and the best possible Z resolution. A premium is placed on the good Z resolution since TOFI has insufficient mass to charge resolution to separate isobars directly.

Masses are extracted from the measured mass to charge spectrum by first determining the charge of each ion. The charge determination begins with an approximate mass calculation for the ion using the total energy measurement, E, and the velocity, v, measured between the first two timing detectors prior to entering the spectrometer (i.e. $m_{lo} \quad 2E/v^2$). Dividing this low resolution mass by the high resolution mass to charge measurement uniquely determines the charge state of the ion. Note that

the charge resolution is governed strictly by the resolution of the total energy measurement and the velocity measurement. In our first measurements we obtained a charge resolution of $\Delta Q/Q \sim 1\%$.

From the above information individual mass–to–charge histograms are produced for a single element with a given charge (see Figure 6). The centroid (in channel numbers) for each mass–to–charge line is then determined using moments analysis. Known mass lines were then fit using a quadratic function to determine the mass–to–charge calibration. In our first experiment approximately 120 mass–to–charge lines were fit with a typical reduced chi square of 1.1. The final mass for each nuclide was determined by taking a weighted average of masses from 1) 30 separate runs and 2) all measured charge states for a given nuclide (typically 2 to 3 charge states were predominant). For additional details see Ref. 8 which describes the first mass measurements using TOFI.

4.0 Conclusion

The overall philosophy that has governed the design, fabrication, and assembly of TOFI has been the elimination of optical aberrations and magnetic field imperfections to obtain the best time–of–flight determination possible. This goal resulted in a simple, isochronous, nondispersive, four cell design in which each cell consists of an integral function dipole magnet. To achieve this goal, the four magnets that make up the spectrometer were individually trimmed and surface coils were included in the design to reduce inhomogeneities introduced by fabrication imperfections. During the first year of operation, the spectrometer achieved a mass resolving power of $M/\Delta M = 2600$, exceeding the design goal by 30 %. Improvements in detector and electronic technologies could permit still higher resolving powers and thus facilitate additional mass measurements with higher precision out to more neutron–rich nuclei.

Acknowledgements

It is a pleasure to acknowledge the excellent contributions of the LAMPF engineering, electronics, and operations groups who helped build the spectrometer and transport line. Special thanks goes to Dr. L. E. Agnew who helped coordinate the various activities of the support groups. We would also like to thank Professor Harald Enge of MIT for help in designing the spectrometer. This work was performed under the auspices of the US Department of Energy.

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Figure Captions:

1. Principal trajectories through TOFI showing that ions of equal mass–to–charge ratios require the same flight times by requiring fast moving ions to take a longer path as compared to slower moving ions. This principle is illustrated by showing the position of particles at five different times with full circles representing ions of mass–to–charge ratios $(m/q)_0$ and kinetic energies E_0 and E_1. Analogously, the open circles represent ions of different mass–to–charge ratio $(m/q)_1 > (m/q)_0$ again with energies E_0 and E_1. This illustrates the basic isochronous property of the spectrometer and how different times–of–flight occur for ions with different mass–to–charge ratios.

2. Photograph of the TOFI spectrometer showing the four dipole magnets. The entrance to the spectrometer is in the stainless steel box located just to the left of the photographs's center and the magnet with the label 4 on its side.

3. Side and top schematics of a TOFI spectrometer magnet. Note the locations of the Rose shims, trimming wedges, and surface coils.

4. Photograph of a quadrupole surface coil lying on the bottom pole tip of one of the dipole magnets. A hexapole coil is located on the opposite side of the printed circuit board and an inhomogeneity surface coil board lies underneath. A similar set of coils was constructed for the top pole.

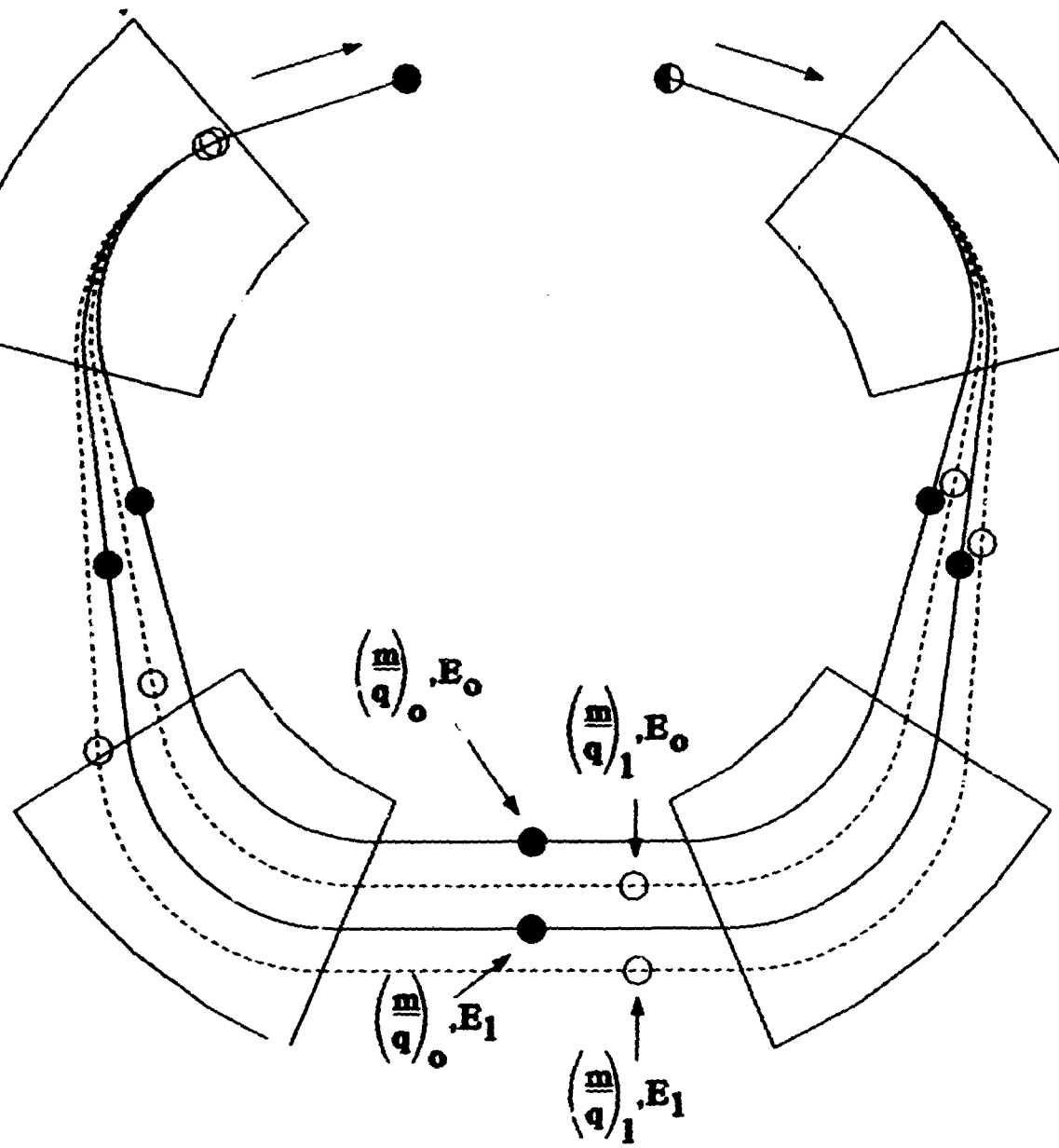
5. Effect of the surface coils on the energy dependence of time–of–flight in TOFI. The main dipole field was set to 3030 G for 5.4 MeV alpha particles. a) All surface coils off. b) Quadrupole energized to 4 A resulting in a maximum additional field of ± 9 G. c) Hexapole coil energized to 2 A resulting in a maximum additional field of 2.5 G. d) All coils optimized.

6. Mass–to–charge histogram for sodium isotopes in a 9+ charge state.

Tables:

TABLE 1. TOFI spectrometer specifications.

Solid angle:	$\Omega = 2.5$ msr
Energy acceptance:	$\delta E/E = 8\%$
Max. magnetic rigidity:	$B\rho_{max} = 0.9$ Tesla-m
	$p/q = \sim 250$ MeV/c/q
Bending radius:	$\rho_o = 1.1$ m
Central flight path:	$L_o = 14.0$ m
Magnification:	$(x, x) = (y, y) = 1$
Mass resolving power:	$M/\Delta M = 2600$


$\left(\frac{m}{q}\right)_o, E_o$
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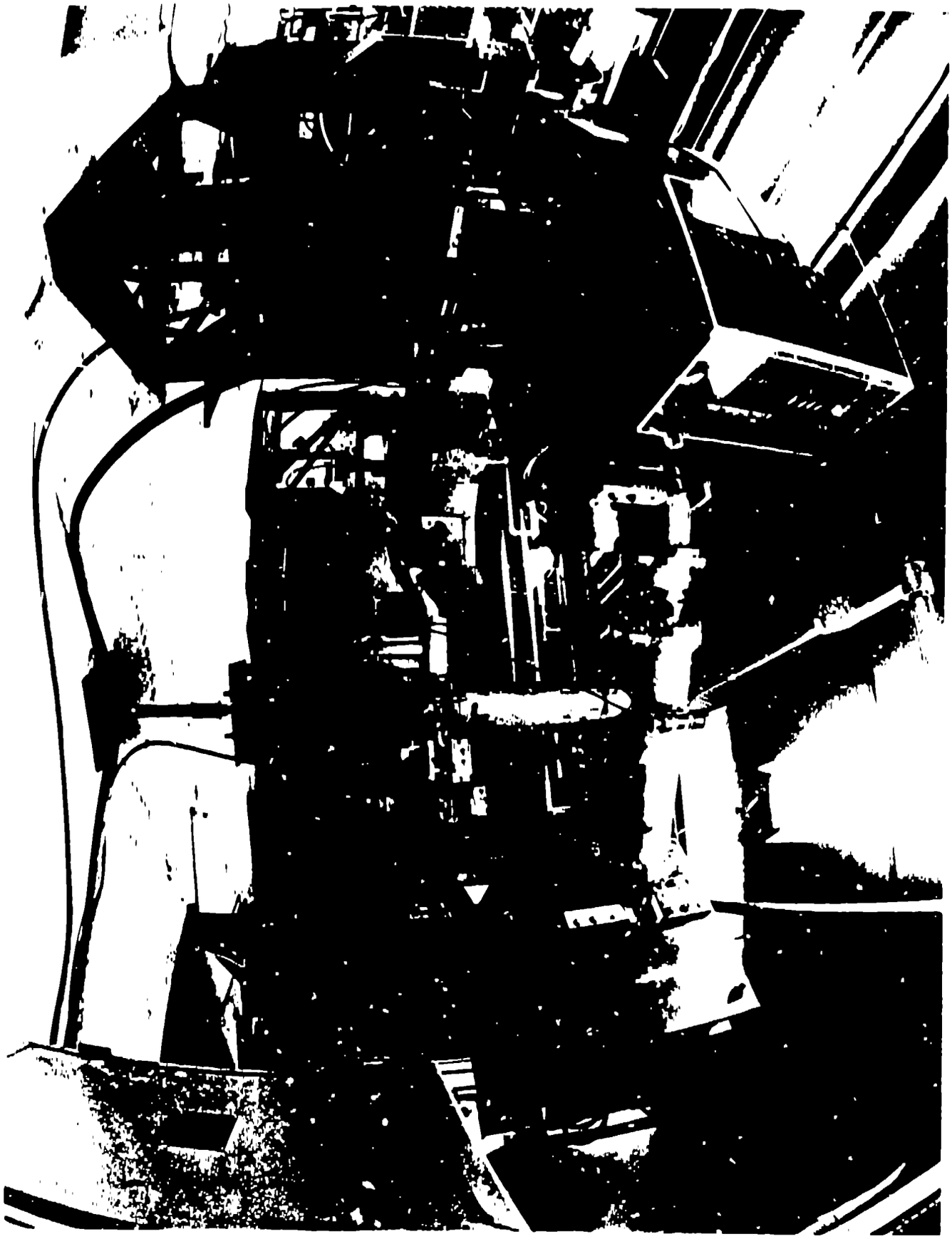
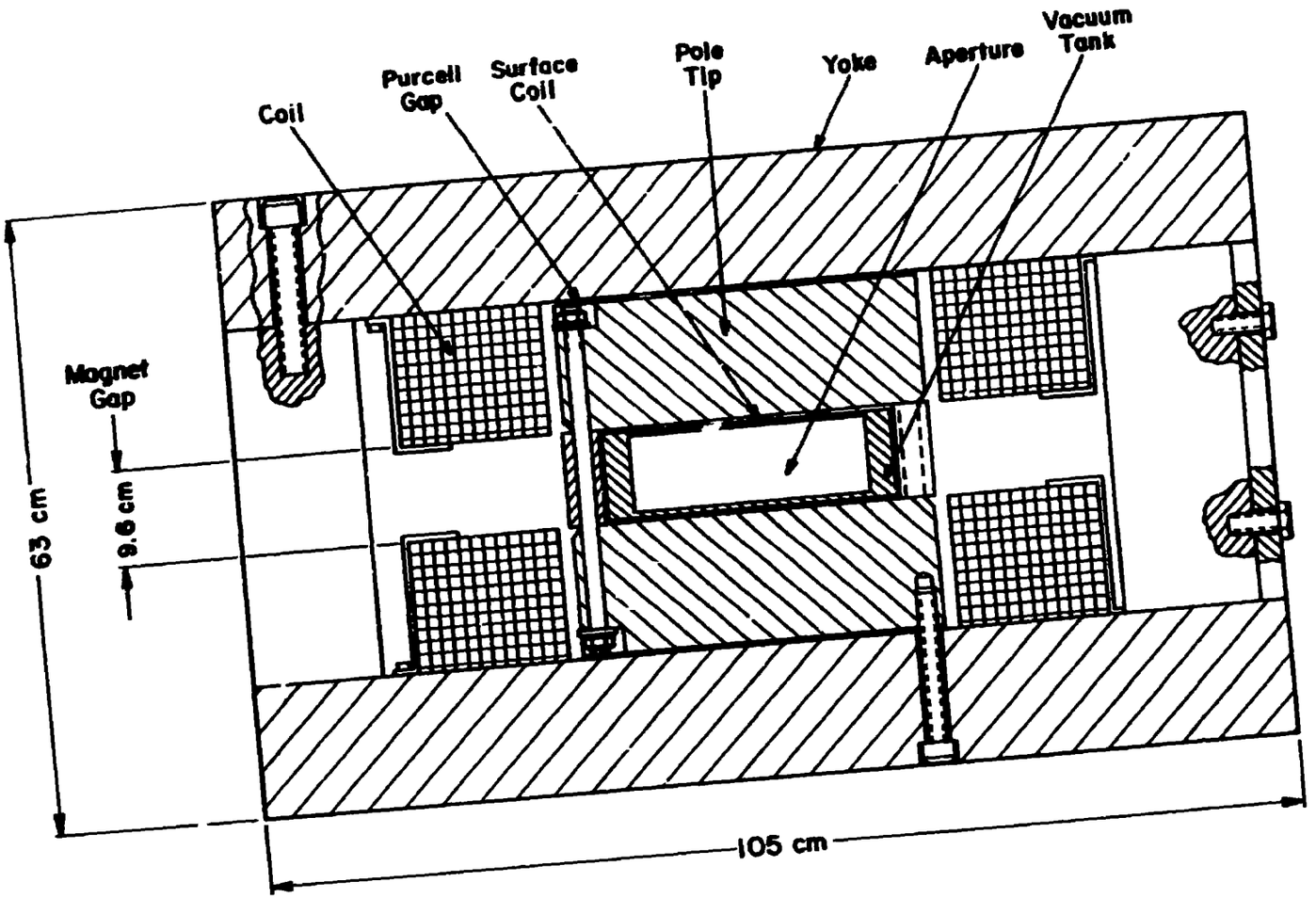
$\left(\frac{m}{q}\right)_o, E_1$
$\left(\frac{m}{q}\right)_1, E_1$

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Surface Coil
Pole Tip
Yoke
Aperture
Vacuum Tank
Magnet Gap
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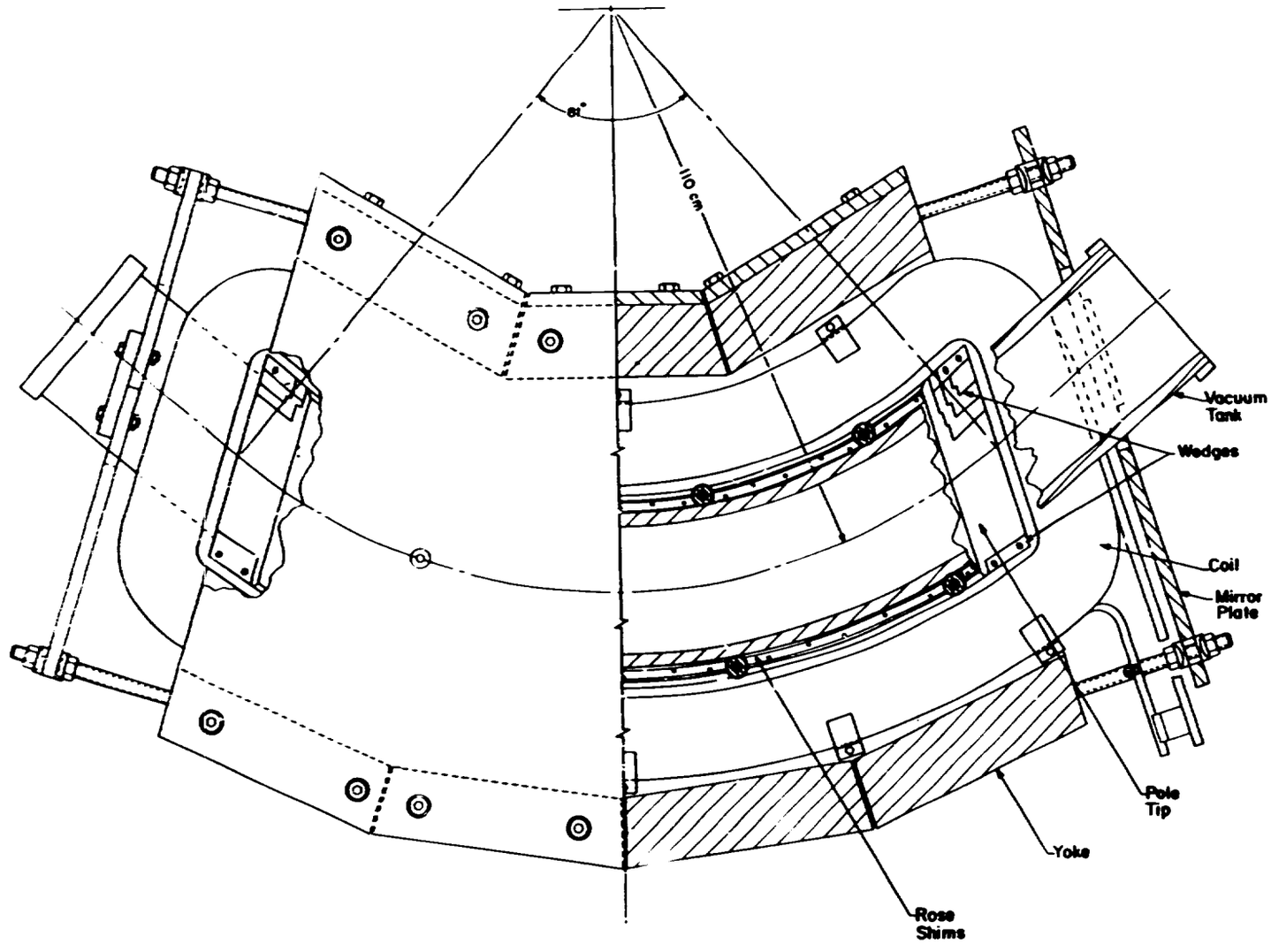
63 cm
105 cm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110 cm
Vacuum Tank
Wedges
Coil
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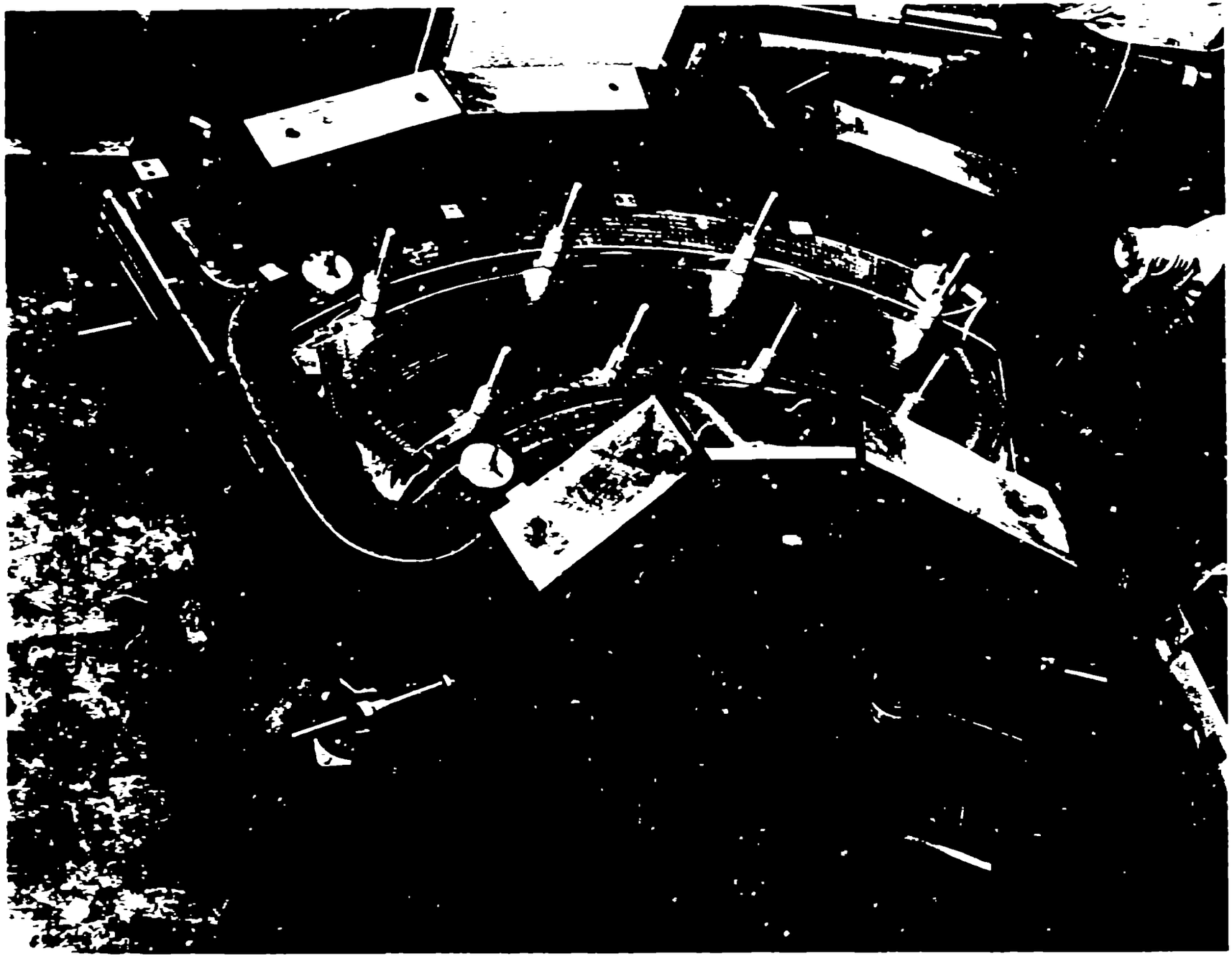
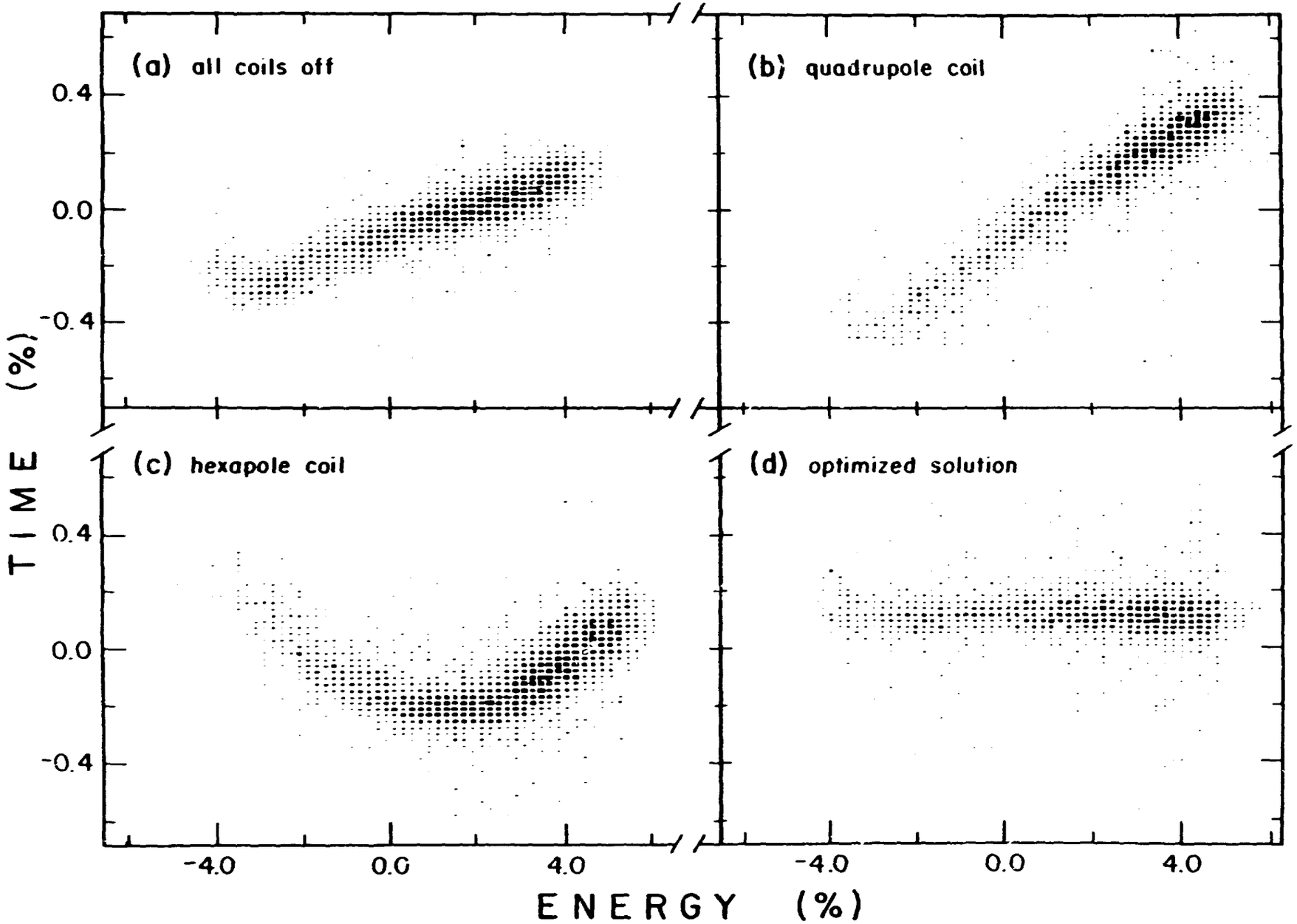
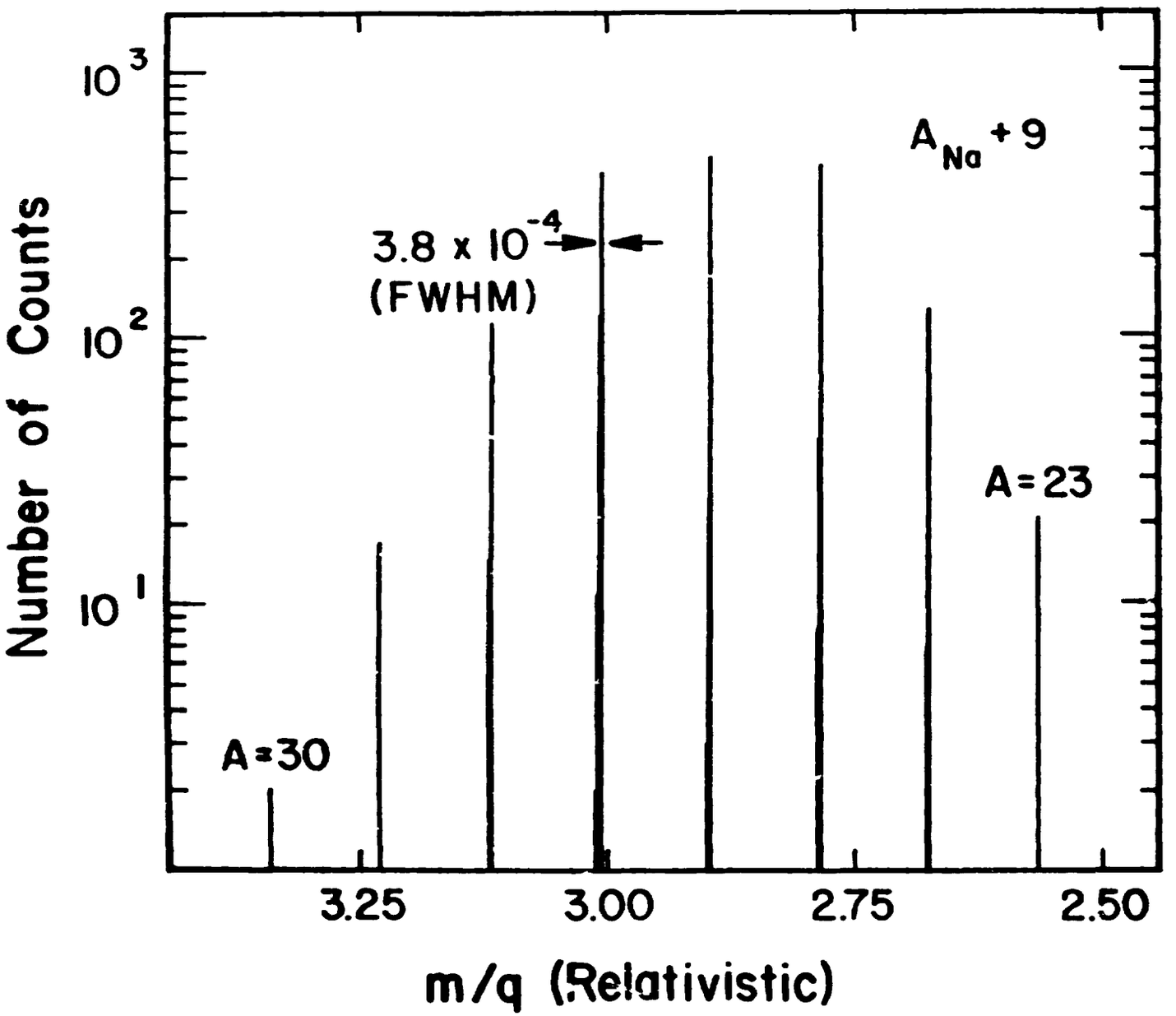
Pole Tip
Yoke
Rose Shims




(a) all coils off
(b) quadrupole coil
(c) hexapole coil
(d) optimized solution
0.4
0.0
-0.4
TIME (%)
-4.0
0.0
4.0
ENERGY (%)


Number of Counts
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10^2
10^1
$A_{Na}+9$
3.8×10^{-4}
(FWHM)
A=23
A=30
3.25
3.00
2.75
2.50
m/q (Relativistic)